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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

THE VON WALTENHOFEN PHENOMENON IN SOFT IRON RINGS.

By Louis A. Babbitt.

With a Plate.

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THE VON WALTENHOFEN PHENOMENON IN SOFT IRON RINGS.

Presented by B. O. Peirce, May 10. Received July 11, 1911.

By Louis A. Babbitt.

The purposes of the investigation described in this paper were two: first, to determine how the manner of growth of a magnetizing field of given final intensity about a mass of finely-divided iron affects the change which the field produces in the magnetic condition of this iron; second, to harmonize the results found by previous observers in the same field of inquiry.

About fifty years ago von Waltenhofen [1] observed that when the field in a solenoid used to magnetize a soft iron rod was suddenly reduced to zero by breaking the circuit, the remanent magnetism of the iron was, under certain circumstances, opposite in direction to that induced by the field just applied. This result, interpreted by means of Weber's theory of elementary magnets possessing inertia, led almost immediately to the conclusion that the magnetic condition of the mass of iron is affected by the manner in which the magnetizing field is built up. If, for example, the field were changed continuously in the same direction, in one instance by two steps and in the other by one, from one given value to another, the one-step method should produce, according to Weber's hypothesis, the greater magnetic change in the iron; for the greater velocity acquired by the elementary magnets under this method would cause them to rotate through a greater angle, and show a greater flux change in the metal. Similarly, a high electromotive force applied to the magnetizing circuit should, through the more rapid magnetization produced, give a larger magnetic change than a low voltage would, even though the final value of the current is the same in both cases.

From a commercial, as well as from a scientific point of view, this phenomenon is important. The calculations which precede electrical

[1] Pogg. Ann., **120**, 650. Winkelmann, Hand. der Physik, **5**, 214.

construction are often based upon hysteresis diagrams or magnetization curves, which are supposed to show the magnetic characteristics of different specimens of iron and steel under given excitations, and, if the forms of these figures depend very much upon the manner of application of the excitations, it is essential that the observations be made under conditions approximately the same as those under which the iron will have to do its work. It is important, therefore, that the engineer should know how closely the test conditions and the working conditions must correspond, and a number of investigators have studied the subject.

At the outset the subject may be divided into two parts : first, the magnetization of large solid masses of iron ; second, the magnetization of finely laminated iron.

For the former it is almost unanimously agreed that, if the change in the magnetizing field is always the same in direction, in going from one value of the magnetic field to another, the manner in which that change is produced affects the total change of flux in the iron. Fromme,[2] Lehman,[3] Gumlich and Schmidt,[4] Heyse,[5] Rücker [6] and B. O. Peirce [7] have obtained results with various shapes of iron, such as toroids, ellipsoids and rods, which show this difference in the flux change to a greater or less extent. Rücker, for instance, found that in the case of soft iron it might amount to 30 per cent of the total flux change. For hard material the percentage was smaller.

In some early experiments I used a large, massive cast iron magnet weighing about 1500 kilogrammes. Its general shape is shown in Figure 1. The base is of rectangular cross-section, 40 cm. by 20 cm., 101 cm. long and 80 cm. high ; the arms are cylinders of steel 25 cm. in diameter and are capped by rectangular pole pieces 4.5 cm. thick and 580 cm. in area. Four coils having a total of 2823 turns and a resistance of 12.4 ohms served for the magnetization.

The time required for the current to reach a constant value in such a system is very appreciable. Two to three minutes was not at all unusual. Such long, slow flux changes taking place in the iron could not be measured accurately by the long-period galvanometer [8] that had been constructed for this sort of work. However, it was found that

[2] Wied. Ann., **43**, 181 (1891); **44**, 138 (1891).
[3] Ibid., **48**, 422 (1893).
[4] Elektroteknische Zeitschrift, **21**, 1900.
[5] Inaug. Diss. Halle, p. 33, 1901.
[6] Inaug. Diss. Halle, 1905.
[7] These Proceedings, **43**, 155 (1907).
[8] These Proceedings, **44**, 1908.

a slight modification of the usual procedure in step-by-step ballistic measurements would give consistent results. Instead of keeping the secondary circuit closed during the whole flux change corresponding to a given step of the primary current, advantage was taken of the slow movement of the amperemeter and, when the current had attained a certain value in the primary, the secondary was broken. The flux change up to that point was recorded with more or less accuracy.

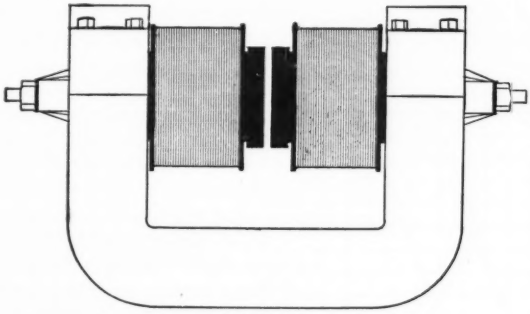

FIGURE 1.

The iron was then carried on around its hysteresis curve, and, when the primary current had reached the same value that it had at the instant when the secondary was broken, the secondary circuit was again closed, and it remained closed during the completion of the step of the primary current, thus giving a ballistic effect which measured the change of magnetic flux during the second part of the step in question. If two minutes are required for the complete flux change and a galvanometer with a period of five minutes be used, a division of the one step into four parts instead of two as just described will give a result having a probable error not greater than 0.4 of one per cent. The sum of the four throws will give the total flux change in that step. The application of this method to the various steps of an hysteresis curve will give results of any desired degree of accuracy up to the limit of the instrument. In fact, numerous tests showed that after the iron had been carried through a cycle a large number of times two successive cycles obtained in this way were equivalent both as a whole and in their corresponding steps to within one half of one per cent.

The three curves A, C, and D of Figure 2, corresponding to 4, 28 and 56 steps respectively, were obtained in the manner just described. The maximum value of the magnetizing current and consequently the maxi-

mum H is the same for all three. In each case the iron was carried around its hysteresis cycle a large number of times. No demagnetization was attempted; the change from one curve to another consisted merely in the change of the number of steps.

The maximum value of B was approximately 6000. The vertical ordinate is in terms of throws of the galvanometer. If one half the throw for a complete reversal of the maximum H be taken as 833, the maximum values of B for the three curves would be represented by 824, 770, and 692; that is, for the introduction of four steps instead of one into the hysteresis curve, the maximum value of B has fallen 1 per cent, for 28 steps 7.6 per cent, and for 56 steps 17.4 per cent.

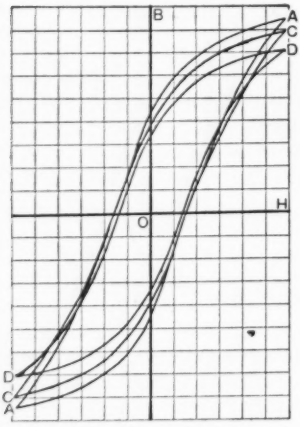

FIGURE 2.

For massive iron therefore it is undoubtedly true that a change in the number of steps of magnetization has a certain measurable effect on the final magnetic condition of the iron.

In such masses of iron the eddy currents can in no wise be neglected. There is nothing to show that the phenomena may not be accounted for by their action as well as by some inherent property of the iron itself; or indeed by both of these causes existing side by side. For more definite conclusions it is necessary to eliminate one of the factors. The former yields the more readily.

It has been shown that in the case of a long cylinder the reduction of the eddy currents[9] can be carried to any desired point by a sufficient lamination of the iron, and a toroid, if the radius of the ring be large enough in proportion to that of the solid mass, presents a form approximating that of a cylinder. While a mathematical demonstration will not be attempted, I think it safe to regard lamination as playing in my toroid the same rôle as in a cylinder, and by the elimination of eddy currents offering a means for deciding to what we are to attribute the effect of variation in the methods of magnetization.

[9] These Proceedings, **43**, 161–182 (1907).

Along this line three investigators have worked Fromme [10] studied the difference in the magnetic condition of bundles of iron wires according as they were in the magnetizing solenoid when the current was applied or were put in afterward. To be sure, he found a difference; but since part of his process included handling the bundles while under the influence of the field it seems to me that we should not accept his

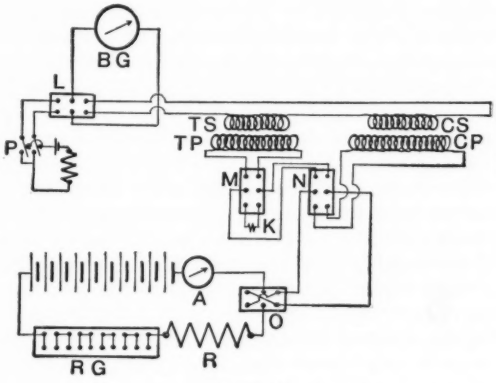

FIGURE 3.

results as conclusive. The jarring [11] and straining of the wires due to the handling might account for them. Rücker [12] took hysteresis curves consisting of various numbers of steps for a small toroid of soft iron wire and observed a decrease in the maximum flux through the iron as the number of steps was increased. For his specimen this decrease was the most pronounced when the induction per square centimeter, B, was about 4000 and amounted then to 6 per cent of the total induction. B. O. Peirce [13] compared step-by-step hysteresis curves of a toroid which had a finely divided core, with similar curves calculated from the manner of growth of the current in the magnetizing coil; an oscillograph supplied the necessary current-curves. Beyond the probable errors of this method he could detect no difference between the two sets of curves.

At present, therefore, we have two diametrically opposed conclusions supported by experiment.

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[10] Wied. Ann., **4**, 76 (1878).
[11] Ibid., **5**, 345 (1878).
[12] Inaug. Diss. Halle, 1905.
[13] These Proceedings, **43** (1907).

The shape of the iron is an important consideration. That all unnecessary difficulties might be avoided, such as would be introduced by the poles of a broken magnetic circuit, the toroid was chosen, for my work, as the simplest and consequently the most suitable form.

The arrangement of the apparatus is briefly as follows. The primary of the toroid, TP, Figure 3, to be investigated, is connected in series with an amperemeter, A, a set of resistance gaps, RG, into which any desired resistance coil could be introduced, a rheostat, R, a reversing switch, O, and a set of ten storage cells. The double switch, N, allowed me to change from the primary of the toroid to the primary of the calibrating solenoid, CP. The switch, M, was for the purpose of introducing a resistance, K, approximately equal to that of the primary of the toroid, when it was desirable to reduce the field in it to zero without breaking for any length of time the flow of current from the battery. This device kept the current more nearly constant than would have been otherwise possible. The secondary circuit consisted of the ballistic galvanometer, BG, in series with the secondary of the toroid, TS, the secondary of the calibrating solenoid, CS, and the switch, L. This last permitted me to throw the galvanometer into the damping circuit. The flux changes produced in the iron core were measured by the throw of the ballistic galvanometer.

Description of the Apparatus.

The usual form of ballistic galvanometer with a period of about 15 seconds is not suited for this work. The total flux change in the toroid is not completed before the coil has swung considerably out of its zero position; and consequently the angular rotation of the coil is no longer proportional to that flux change. For my purposes I constructed an instrument similar to one used by Professor Peirce.[14]

The coil of the galvanometer, which was of the Ayrton-Mather type, was loaded by two brass balls to increase its moment of inertia. The whole was suspended by steel gimp; the current was conducted to and from the coil, of which the ends were soldered to the two vertical wires, by spirals of copper gimp similarly attached.

The increase in the inertia of the suspended system due to the two brass balls increased the period of the galvanometer in this instance to 65 seconds. As it was found by experiment that, if the secondary circuit were closed one half a second after the primary circuit, there was no perceptible deflection of the galvanometer, the period was re-

[14] These Proceedings, **44**, 283 (1909).

garded as sufficiently great to register within the accuracy of the instrument the flux change that took place.

The throw was read by means of a telescope and scale; the distance of the latter from the mirror was 86 cm. Since the total possible deflection on either side of the zero amounted to 23 or 24 cm., it was necessary either to compare angles calculated from the deflection or to compute the angles for one set of deflections, add them, and determine the single deflection corresponding thereto. In other words, for throws of more than ten centimeters it was not admissible to regard the deflection as proportional to the flux change in the toroid.

The calibration by means of the standardizing solenoids showed that the throw could be obtained consistently, for any given quantity of electricity sent through the instrument, to within 0.1 mm. Thus for throws greater than 10 cm. 0.1 per cent and often 0.05 per cent was the accuracy attained. For such agreement three things were absolutely essential: the suspended system must be at rest before the throw commenced; the throw must be taken always in the same direction; the coil, in coming back, must never swing more than a few millimeters beyond its zero position. If it did go far beyond, the zero point was changed and the next deflection or two were not quite what they should be; usually too large. In this connection, too, it was observed that the first two and sometimes three throws taken in the day's work were in general larger than those that followed by a fraction of a millimeter; they were always thrown out of each set of results as doubtful. Although the care of complying with all the conditions made it necessary to spend from three to six hours in taking the data for any one of the curves presented later the accuracy of the results seemed to make it worth while.

One more peculiarity came out during the investigation. When the current in the primary of the calibrating solenoid was simply broken, instead of reversed as usual, and the deflection for the reversal calculated from the resulting throw, this was in general a few tenths of a millimeter greater than an observed deflection for a reversal. The difference appeared only when the total reversal gave a throw of more than 12 or 14 cm. It seemed as if somewhere in the secondary circuit there must be a slight leakage produced by the higher voltage of the complete reversal. In order to be sure of the amount of this difference a full reversal was taken in the calibrating test before each day's work as nearly as possible equal in throw to that produced by the reversal of the field to be used on the toroid during the day; then the throw was observed when the same current was broken, and the error calculated. It was hoped that the conditions in the secondary circuit

when the current in the solenoid was reversed would be sufficiently like those existing when the field of the toroid was reversed to give the same leakage. As a matter of fact, the difference between the calculated and observed reversals for the solenoid were throughout so nearly equal to the corresponding difference when a reversal consisting of a number of steps was compared with a complete reversal of the field in the iron, that in all probability the conditions were approximately the same and the leakage likewise. Unfortunately this leakage was not taken into account at first because of the other greater inaccuracies then occurring in the work; it is applied, therefore, only to the work done on coils I and III, not to II.

The amperemeter was supplied with a number of shunts so that the constancy of the current could always be determined to within 0.1 per cent, and as a general rule more closely than that. It did not appear to be necessary to measure so exactly the true value of the current used; and no attempt was made to do so. However, it was given by the instrument within 0.5 per cent.

The resistances in the primary circuit were made of constantan wire set in enamel. For the moderate currents used, seldom over two amperes, their rise in temperature did not have any appreciable effect.

The primary and secondary solenoids used in calibrating the ballistic galvanometer were both carefully made. The primary consisted of 5526 turns of No. 18 B. & S. annunciator wire wound on a brass tube split longitudinally. The total length of the coil was 176.2 cm. The secondary consisted of 538 turns of well insulated wire wound on a wooden core. The primary was attached to the wall vertically at a distance of 15 feet from the galvanometer; inside it and equidistant from either end was hung the secondary. This arrangement being always constant allowed the testing of the galvanometer at the beginning and end of the day's work, and showed immediately whether any change had occurred.

Except for soldered joints the secondary was throughout a copper circuit. Thus all trouble from thermoelectric currents was eliminated.

Three toroids were used which for convenience we may designate as I, II and III. The second was the first to be experimented on, but the meaning of its data will be clearer if discussed after the more extensive investigation with toroid I.

The core of I was made out of carefully annealed soft wire. After the winding, the wires were insulated from each other by soaking the whole in shellac and drying it. A layer of paper covered the core; on it was wound a single layer of secondary divided into four parts. A second layer of paper, the first layer of the primary, a third layer of

paper, and the second layer of the primary, followed in the order given. Care was taken to make the winding as uniform as possible. The data for the toroid are as follows:

Average diameter of the iron wire of the core	0.0254 cm.
Number of turns of iron wire in the core	600
Weight of iron in the core	98.23 gm.
Area of cross-section of the iron in the core	0.303 sq. cm.
Average radius of the iron ring	5.6 cm.
Secondary, 4 coils, No. 26, double silk insulation,	
Coil A	50 turns.
Coil B	75 turns.
Coil C	100 turns.
Coil D	340 turns.
Primary, 2 layers	
First layer	164 turns
Second layer	157 turns

The core II consisted of iron wire not so well annealed as that of I. Insulation was obtained by dipping the wound core into hot paraffine. The primary and secondary were put on with the same precautions as to paper insulation and the uniformity of winding as in the case of toroid I. The data for II are:

Average diameter of the iron wire of the core	0.0285 cm.
Number of turns of iron wire in the core	500
Weight of iron in the ring	88.1 gm.
Area of cross-section of the iron ring	0.318 sq. cm.
Average radius of the iron ring	5.55 cm.
Secondary, 4 coils, No. 26, double silk insulation,	
Coil A	157 turns.
Coil B	146 turns.
Coil C	154 turns.
Coil D	131 turns.
Primary, 2 layers,	
First layer	160 turns.
Second layer	160 turns.

The core of III [15] weighing 55 lbs. consisted of wire approximately one third of a millimeter in diameter. Insulation of the iron was effected by means of paraffine. The larger wire used for both primary and secondary afforded by its double insulation complete freedom from any appreciable leakage.

[15] The same core was used by B. O. Peirce: These Proceedings, **43**, 5 (1907).

The demagnetization of toroids I and II was carried out in one of two ways. In one process the toroid was left with its primary in the primary circuit, Figure 3. By means of the reversing switch the field was reversed and after each reversal decreased by the addition of resistance from the rheostat and the gaps provided for that purpose. When the current had been reduced to about 0.1 of an ampere the toroid was disconnected and attached to the secondary of an alternating current transformer. This was movable and could be pulled along a track away from the primary which was connected to the 110-volt, 60-cycle lighting circuit. The further demagnetization was carried out in this manner.

The second method consisted of the introduction into the primary circuit, Figure 3, of a piece of apparatus designed to reverse the current automatically. The main features were a motor and four rods joined to the motor through gears and cranks. The cranks lowered the rods by pairs into mercury cups beneath. With one pair of rods in contact with the mercury, and with the proper electrical connections from the toroid to the rods, and from the mercury cups to the battery, the current flowed in one direction through the toroid; when the motor was turned until these two rods were raised and the other pair were in contact, the current flowed in the opposite direction. The running of the motor together with the introduction of resistance into the main circuit resulted in the demagnetization of the toroids. By keeping the amperemeter in the circuit it was possible to regulate the demagnetizing current so that it should never be above that already applied to the toroid. This is a distinct advantage over the first method, in that the history of the iron is better known and the effect of its previous magnetic history more easily determined. With the motor running so as to give three or four reversals of the field in the toroid per second, the resistance was introduced gradually from the rheostat and gaps until the current was not above 0.0003 ampere. The time given to one demagnetization by this device was between two and three hours.

The Investigation of Toroid I.

The primary and secondary of the toroid were connected with their respective circuits as shown in Figure 3. If M and the other switches be set so that the current flows through K, and if, after the core has been demagnetized, M be thrown over, the throw of the calibrated galvanometer will give means of calculating the B induced in the iron. Let the current be reversed by O while the secondary circuit is broken

at L; make the secondary again at L and reverse O. The B calculated from this last throw will be in general different from the first B. If one repeats the process, amounting to carrying the iron around the hysteresis cycle, a sufficient number of times, it will be found that the value of B will become constant or at any rate very nearly so. Instead of computing B it will be just as satisfactory to compare directly the throws of the galvanometer. This will be done throughout the work.

Any one of the complete reversals just described will be referred to as a 1-step reversal. A 3-step reversal will consist of the following process. With a maximum of the flux in one direction at the start, the current is broken by throwing over M and thus putting K in the circuit. After the introduction of resistance and the reversal of O, M is thrown back to the primary of the toroid. Finally the resistance just introduced is cut out, by moving a rheostat arm, if it be in the rheostat, or by short-circuiting a coil, if it be in one of the gaps. For each of these three steps the flux change is recorded as a throw of the galvanometer. The angular displacement of the coil can be computed and from the sum of these angles the corresponding single throw in centimeters. By correcting for leakage one has the single throw that can be used as a basis for comparison. A 7-step reversal would consist of seven steps between the two flux maxima, and so on.

The result of carrying out such an operation is to go from one magnetic condition to another in a given number of steps. If the initial conditions be twice the same and the final inducing field twice the same, but the number of steps in one case different from that in the other, there are at hand the means for determining, by comparing the corresponding single throws of the galvanometer, what effect the number of steps has on a magnetic change. To satisfy the second of the two conditions is a comparatively easy matter. The first is more troublesome. However, if the iron be carried through a large number of hysteresis cycles, until the maximum B for the cycle is constant, a number of observations taken for 1-step reversals and then a number for 3-step reversals, it is certain that for the first 3-step reversal the initial conditions were the same as for the last 1-step reversal. Furthermore, if the following 3-step reversals give the same result as did the first 3-step reversal, it is fairly safe to assume that there has been no change in the iron after the first 3-step cycle. For two low values of H, 2.35 and 3.46, this process was carried out; the corresponding maxima for B were 820 and 1394.

In the first case, after the ballistic galvanometer was found to be working with its usual accuracy (0.1 per cent), the iron was carried through twenty-five 3-step reversals with a maximum field of 2.35.

The following observations were taken for the 26th and 28th reversals one 3-step reversal coming between the two. No measurements are here recorded for the odd-numbered reversals, which were, of course, in the opposite direction to the even-numbered ones.

Rev.	Amp. Read.	Ball. Galv.	Corresponding Single Throw.
26th	8.90 0.00	4.12	
	0.00 5.94	4.07	10.53
	5.94 8.90	2.31	

Rev.	Amp. Read.	Ball. Galv.	Corresponding Single Throw.
28th	8.90 0.00	4.12	
	0.00 5.94	4.07	10.55
	5.94 8.90	2.33	

The 29th to the 82d were 1-step reversals. Of these the 30th, 32d, 80th and 82d are recorded.

Rev.	Amp. Read.	Ball. Galv.	Average Throw.
30th	8.90	10.55	10.55
32d	8.90	10.54	
80th	8.90	10.51	10.51
82d	8.90	10.51	

The difference between the average of the twenty-seven even-numbered reversals, 30th–82d, and the average of the first two recorded 1-step reversals, 10.55, is 0.1 per cent. The flux change per reversal has decreased slightly, from 10.55 to 10.51, during the course of the 3-step reversals. That this is characteristic of the specimen during its early magnetic history will appear from the data following.

In this case the maximum value of H is 3.46, of B 1394. Thirty 3-step reversals were taken and then the 31st and 33d observed.

Rev.	Amp. Read.	Ball. Galv.	Corresponding Single Throw.
31st	13.27 0.00	6.45	
	0.00 8.26	8.40	23.06
	8.26 13.27	7.75	

Rev.	Amp. Read.	Ball. Galv.	Corresponding Single Throw.
33d	13.27 0.00	5.89	
	0.00 8.26	7.95	23.06
	8.26 13.27	8.75	

A set of 1-step reversals followed the 33d, out of which four are recorded.

Rev.	Amp. Read.	Ball. Galv.	Av. Throw for Galv. Read. 13.27.
35th	13.27	23.01	22.99
37th	13.26	22.94	
87th	13.26	22.56	22.58
89th	13.26	22.59	

Here the 1-step reversals give a smaller "throw," indicating a smaller flux change, than the 3-step reversals, but it is to be noted that the first 1-step reversal gave a throw very nearly as large as that given by the 3-step reversals, though the general tendency of the 1-step reversals was to reduce the throw.

A demagnetization and reversal of the order of steps, that is, putting the series of 1-step reversals first, yielded the following. Three of the first 55 reversals are recorded.

Rev.	Amp. Read.	Ball. Galv.	Average Throw.
51st	13.26	22.53	22.55
53d	13.26	22.57	
55th	13.25	22.56	

Of the 52 3-step reversals that followed the 1-step two are recorded.

Rev.	Amp. Read.	Ball. Galv.	Corresponding Single Throw.
105th	13.25 0.00	6.40	
	0.00 8.26	8.32	22.50
	8.26 13.26	7.34	
107th	13.26 0.00	5.91	
	0.00 8.26	7.94	22.50
	8.26 13.27	8.22	

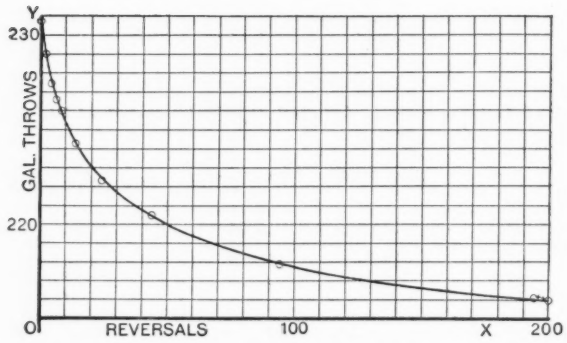


FIGURE 4. Set II: B 6000: first magnetization; all 1-step reversals except the 196th and the 198th, which are 3-step.

Again there is a very slight fall in the maximum B as the number of reversals increases. The 3-step and 1-step processes yield the same results to within 5 parts in 2250.

From these three sets of data it is evident that the effect of the method of magnetization is, in so far as the number of steps is concerned and these tests are carried, of no consequence. In the worst case the difference between the total flux change for 1-step and 3-step reversals is one third of one per cent, and in the best one tenth of one per cent.

It is important to note that such a statement applies only when the iron has reached such a state that it passes repeatedly through

practically the same hysteresis cycle. For the first eight or ten reversals the cycle is changing rapidly and it may well be that, with the iron in that condition, the number of steps taken in going from one value of H to another does effect the final value of B. As it is of interest to settle this question too, the method of investigation must be changed somewhat.

Instead of reversing the field a large number of times before observing the throw of the galvanometer, let the throw be observed when the field is first applied and thereafter for every reversal. If the first throw be regarded as the zero reversal and be doubled in order to make it comparable with the others, a throw-reversal curve may be plotted as shown in Figure 4. Now, with due care that the demagnetizing current shall not rise above the magnetizing current just used, let the toroid be demagnetized by the motor attachment. Another throw-reversal curve taken exactly as before will show the manner in which the iron approaches a constant maximum of B on the second magnetization. A set of such curves giving the behavior of the iron on the first, fourth fifth, sixth, seventh, and eighth magnetizations are those of Figures 4, 5, 6, 7, 8, and 9 respectively.

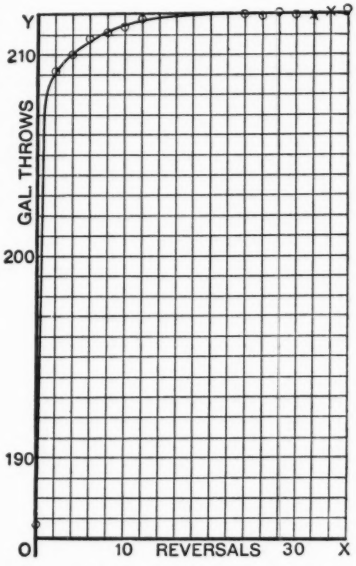


FIGURE 5. Set II: B 6000: fourth magnetization; all are 1-step reversals except the 32d and the 34th, which are 3-step.

It is evident that no two of the curves are exactly alike. The first shows a sharp fall of the maximum B as the field is reversed. On the other hand the second shows a rather rapid rise, as do the remainder. Even so, it is not possible to pick out the same reversal on any two consecutive curves and expect them to register the same flux change except by chance. This is true when the curves examined consist entirely of 1-step reversals up to and including the reversal in question.

It is, therefore, out of the question to expect any consistency in results obtained by comparing reversals if a process of demagnetization intervenes. If 1-step reversals on two successive curves are not comparable and, so far as can be seen, follow no exact law, it is not logical to obtain a hysteresis curve of a given number of steps, demagnetize the iron, obtain a second curve of a different number of steps, and, because the maximum B of one curve is greater than that of another, declare that the number of steps affects the magnetic condition of the iron.

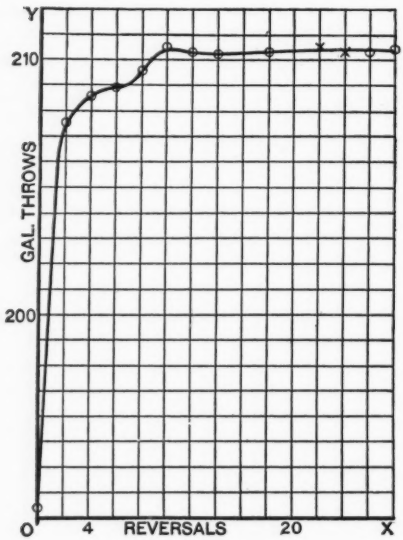


FIGURE 6. Set II: B 6000: fifth magnetization; O indicates 1-step reversals; × 3-step reversals.

This variation in magnetic condition is due, I suppose, to the past history which theoretically can never be twice exactly the same. It may depend on the previous magnetizations or demagnetizations or on both. No complete distinction between the effect of the two is possible, but some few things appear to be true. The remarkable drop in the first curve and rise in the second followed by the more rapid rise in the later curves seem to show the result of previous magnetic history, in particular, the previous magnetizations. For as the number of magnetizations increases, the curves assume more and more the same general form. The variations in the number of reversals required for any particular magnetization to reach a constant state, even after the form of the curve remains unchanged, leads one to suspect that the demagnetization plays an important part. If the iron be treated on each occasion with the same magnetic field, the process of demagnetization is practically the only variable. In it the number of reversals for any given magnetic field and sometimes the number of steps used varied considerably. There is no reason for supposing that a change in the demagnetizing

process would not affect the non-magnetic condition. This is the initial condition for the next magnetization and, if not twice the same, might well be the cause of the variations observed in the early part of the magnetization-reversal curves. It seems to be the more probable cause, inasmuch as the previous magnetizations were pretty nearly alike and would be expected to give less haphazard variations than were actually observed. If the demagnetizing process for any given maximum of B, or at any rate that part of it which affected appreciably the non-magnetic condition of the iron, were carried out always in the same manner, I am inclined to believe that in most cases the sixth or seventh magnetization-reversal curves would be duplicated by those that followed. However, it seems to be impossible to obtain a second time the magnetic condition exhibited, for a given maximum of B, by any point of the first few curves. The same value of B might be obtained, but that does not mean the same magnetic condition; for the next reversal in the two cases would yield distinctly different values of B.

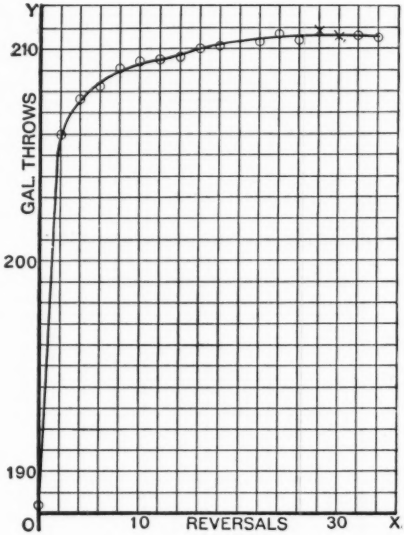


FIGURE 7. Set II: B 6000: sixth magnetization; ○ indicates 1-step reversals; × 3-step reversals.

The tedious process of making each demagnetization the same was not suited to the apparatus at hand and would require a large amount of time and trouble. Furthermore, the relative effect of the various parts of the demagnetizing process on the non-magnetic condition is practically unknown. These two facts eliminated for the present a continuation of the work by the comparison of any two curves separated by a process of demagnetization. Even such knowledge as I have indicated would be of no avail for the first few curves of a set, where it is probably impossible to duplicate any point of the magnetic condition.

The only method applicable was the following. In taking any one of the magnetization-reversal curves by 1-step reversals, for instance curve 7 (Figure 8), the observer introduced at one or two places, as at the fourth and fourteenth reversals, a reversal consisting of a larger number of steps. If the curve be plotted from 1-step reversals only and, after it has been drawn, the other reversals marked in their proper places, some conclusion as to the effect of the latter can be established. The case in which the iron has attained a constant cyclic change has been discussed; it is evident that for that condition this method will decide at once whether or not the number of steps has any effect. If the iron is still in the stage of variation, the early part of the curve, one cannot be so sure. However, if there is no abrupt change in the direction in going from the 1-step reversal just before the 3-step to that just following, and if the 3-step lies to within the expected error on the curve, it seems highly probable that the number of steps is immaterial. If the general shape of the curve in that region is about like that in the corresponding regions of the curves preceding and following, where the region consists wholly of 1-step reversals, the probability is correspondingly increased. Of course, no such similarity as this exists for the first three curves of a set with moderate flux density.

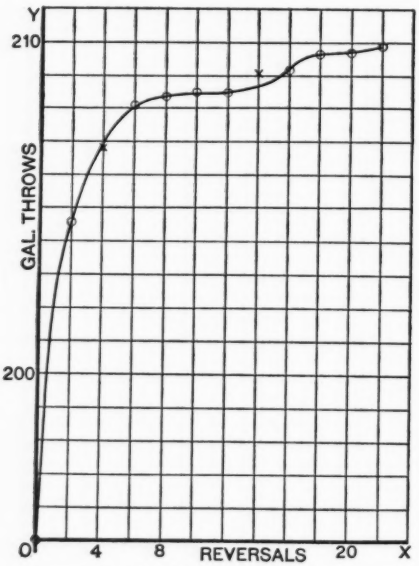


FIGURE 8. Set II: B 6000: seventh magnetization; ○ indicates 1-step reversals; × 3-step reversals.

The method of attack that has been outlined was carried out for approximately the following values of B per square centimeter, 3000, 6000, 7400, 10,100, 13,500, and 19,300, in the order named, and the data obtained have been plotted, in six sets, giving the curves shown.

There is no object in introducing all of the data; but as a typical example I select the fourth magnetization curve for B = 7400, Figure 13, and give both the data and method of treatment in full.

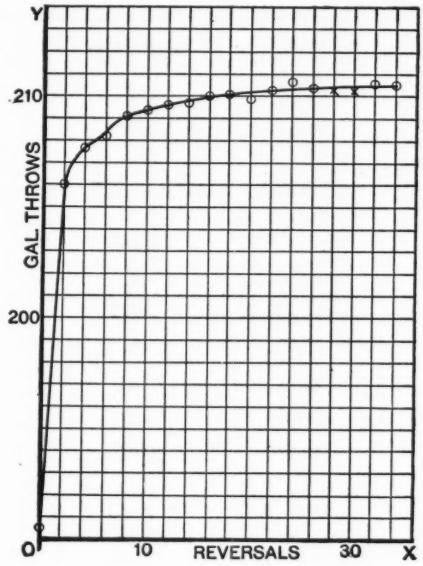


FIGURE 9. Set II: B 6000: eighth magnetization: ○ indicates 1-step reversals; × 3-step reversals.

TYPICAL SET OF DATA.

The toroid has been demagnetized by the motor reverser. The process occupied about three hours and ended when the current had been reduced to 0.0003 amp.

The temperature of the room at the beginning was 18.5° C.

TEST OF BALLISTIC GALVANOMETER.

Reading of Amperemeter.	Throw on Reversing Current.	Reading of Amperemeter.	Throw on Opening Circuit.
7.16	16.77	7.15	8.29
7.16	16.78	7.16	8.31
7.16	16.76		

Average observed throw for reversal of current 7.16 is 16.78. The average calculated throw for the reversal of the current 7.16 is 16.77. These two values were so close that it was assumed that in this instance there was no leakage.

DATA FOR MAGNETIZATION-REVERSAL CURVE.

No. of Rev.	Reading of Amperemeter.	Throw of Ball. Galv. in cm.	No. of Steps in Reversal.
0	13.63	7.53	1
2d	13.63	16.61	1
4th	13.63	16.68	1
6th	13.63 to 0.00	1.70	5
	0.00 to 6.09	2.475	
	6.09 to 7.91	2.95	
	7.91 to 11.04	7.02	
	11.04 to 13.68	2.375	
8th	13.68	16.87	1
10th	13.67	16.90	1
12th	13.67	16.92	1
18th	13.67	16.94	1
20th	13.67 to 0.00	1.69	5
	0.00 to 6.09	2.465	
	6.09 to 7.91	2.95	
	9.91 to 11.03	7.265	
	11.03 to 13.67	2.385	
22d	13.67 to 0.00	1.67	5
	0.00 to 6.09	2.47	
	6.09 to 7.92	2.94	
	7.92 to 11.04	7.32	
	11.04 to 13.67	2.37	
24th	13.67	16.97	1

All odd numbered reversals were 1-step reversals.
The toroid was demagnetized and the galvanometer tested again.

TEST OF BALLISTIC GALVANOMETER.

Reading of Amperemeter.	Throw on Reversing Current.	Reading of Amperemeter.	Throw on Opening Circuit.
7.18	16.81	7.18	8.35

The temperature of the room at the end was 18.3° C.

The temperature of the room dropped gradually during the course of the work. However, as three hours were required for the completion of one such set of data, the change was very gradual, and owing to the care taken to keep windows, doors, and heating appliances unchanged during that period and for some time before it, the rate of the drop was practically constant. This would prevent anything more than a gradual change in the iron or the galvanometer and could not be regarded as the cause for any sudden variation in the curve.

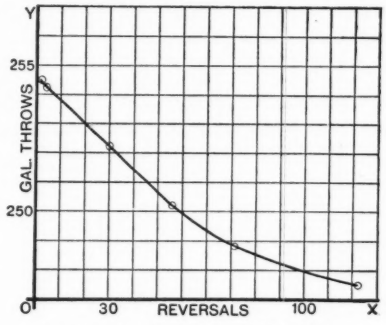


FIGURE 10. Set I: B 3000: first magnetization; ○ indicates 1-step reversal.

The galvanometer, as usual, showed that it could be relied on to give an accuracy of 0.1 of a per cent. The difference between a throw for a reversal, 16.77, calculated from breaking the primary circuit of the testing solenoid, and the observed throw for a

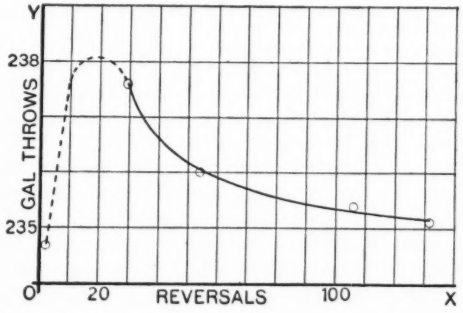


FIGURE 11. Set I: B 3000: third magnetization; all 3-step reversals.

reversal, 16.78, shows that there is in this case practically no correction for leakage. In fact the leakage seemed to occur only when most of the secondary of the toroid was in use. If one were not willing to make

this correction on the ground that it might not be the same for the reversal of the solenoid as for the reversal of toroid, one would find occasionally the reversals consisting of the larger number of steps giving a slightly greater flux change than the 1-step reversals. I have made the correction wherever it entered.

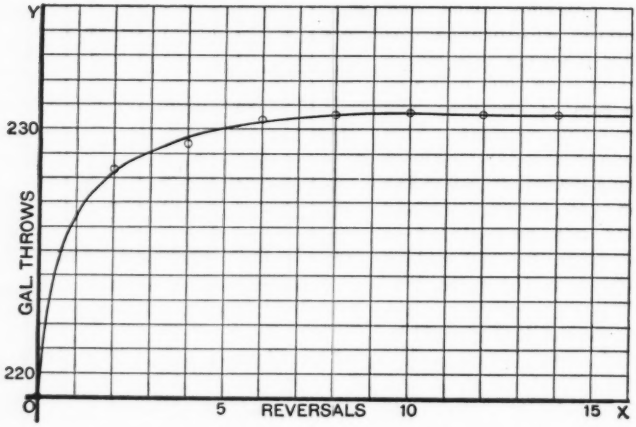


FIGURE 12. Set I: B 3000: tenth magnetization; O indicates 1-step reversals.

The throw, 7.53, due to the first application of the field was expressed in terms of degrees, doubled and changed again to a throw in centimeters in order that it might be on the same scale as the reversals. It is plotted as the zero reversal.

The 6th, 22d, and 24th are 5-step reversals. For each separate step of each of these the angular displacement of the coil was calculated. The five angles of any one reversal were added and turned again into centimeters throw of the galvanometer. A curve, Figure 13, was plotted from the 1-step reversals; millimeters were plotted throughout instead of centimeters. The 5-step reversals were added after the curve had been drawn in order that any variation might appear more plainly.

All the curves of the following six sets were obtained by the same method.

Discussion of the Curves.

Throughout, the reversals consisting of more than one step fall, with very few exceptions, to within 0.1 of a per cent on the 1-step curves. The exceptions occur where they are to be expected, namely, where there would be, with 1-step reversals only, fairly sharp changes in the direction of the curves.

A difference between the first magnetization-reversal curves and those that follow for the same maximum of B appears in each set. It is most noticeable for moderate values of B, from 4000 to 6000. In this region the first two or three curves of a set are of a decidedly different character; the fall in the induction as represented by the first seems to be characteristic, as does the rise and fall in the second and third magnetizations. The curves for the higher inductions show the rise and fall in the first curve and not a fall starting immediately. For any maximum of the induction the last curves of a set take on the same general shape — a sharp rise to a constant maximum value.

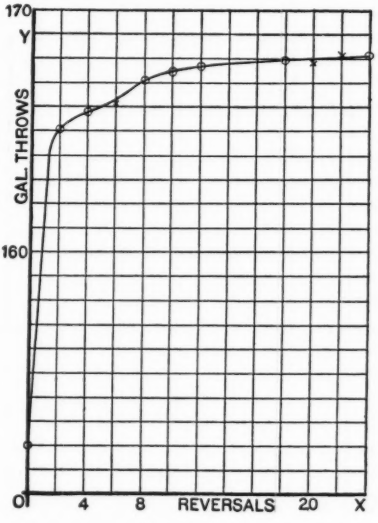


Figure 13. Set III: B 7400: fourth magnetization; ○ indicates 1-step reversals; × 5-step reversals.

The point brought out earlier becomes still more prominent and conclusive. It is that a comparison of the correspondingly numbered reversals on any two successive curves cannot be relied on for definite or decisive conclusions as to the effect of various processes of magnetization or production of the hysteresis cycle. It may be that if one chose those parts of the curves which indicated a constant value of B, the comparison would be of some value; but even here there is room for doubt.

The Investigation of Toroid II.

Coil II occupied the same position with respect to the circuit, (Figure 3,) as did coil I; the secondary was in series with the ballistic galvanometer and the secondary of the calibrating coil, the primary in series with the amperemeter, rheostats, and storage cells.

The method of demagnetization was that first used, the reversing switch (Figure 3), and the alternating current transformer. Certain features of the latter are important. The secondary could not be drawn continuously away from the primary without reducing the demagnetizing fields more rapidly than was deemed advisable. Hence it was moved a short distance and allowed to rest a few seconds. This reduced the field by steps and in such a manner that both the total number of steps and the number of reversals in each step were not regulated even roughly. Consequently no two magnetizations were exactly alike or approximately alike. In other words, the history of the iron just previous to what we have regarded as the initial condition, was subject to variation. It would be strange if the initial condition were not affected by this variation. In that case the result of the first application of the field to the iron after one demagnetization might well differ from that obtained by the first application after the next demagnetization.

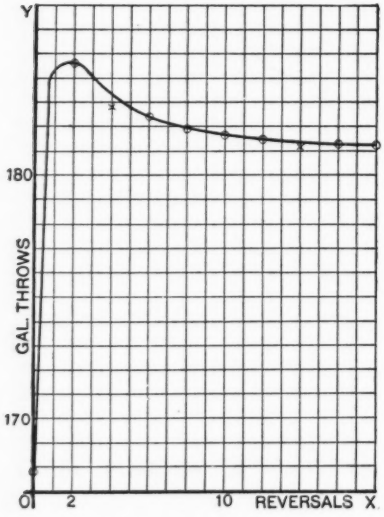


Figure 14. Set IV: B 10,100: first magnetization; ○ indicates 1-step reversals; × 5-step reversals.

The work on this coil was done before that on coil I, but as the results can be discussed more readily by reference to the more extensive data on the latter it was thought best to treat them in this order. The objection to any extended investigation with coil II lay in a weak consequent pole discovered at one point in the ring. The difficulties

in the way of experimentation were sufficiently great without unnecessary additions, the effect of which was unknown; thus immediately after the discovery, core II was discarded and core I made.

The first two sets of data given below were taken in the following manner. The iron was demagnetized and the galvanometer tested. Then the magnetizing field was applied in one or more steps, as is indicated. A repetition of this process yielded the data under discussion. It is to be observed that the flux change recorded is that taking place when the iron is carried from zero magnetization to the first peak of the hysteresis curve.

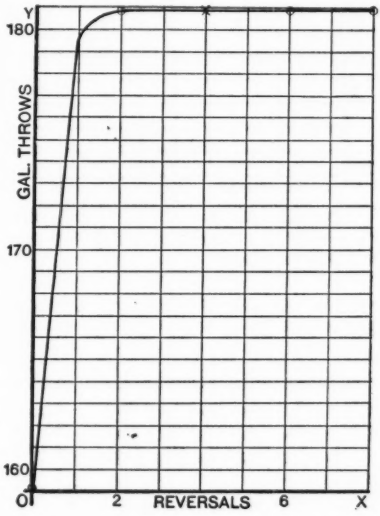


FIGURE 15. Set IV: B 10,100: second magnetization; ○ indicates 1-step reversals; × 5-step reversals.

FIRST SET OF DATA.

The iron was demagnetized.

TEST OF GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.80	21.54
13.81	21.60
13.81	21.59

The iron was demagnetized by transformer and the field built up in one step:

Amperemeter Reading.	Ballistic Throw.
1.220	20.76

The iron was demagnetized and the field built up in one step:

Amperemeter Reading.	Ballistic Throw.
1.220	20.76

The iron was demagnetized and the field built up in two steps:

Amperemeter Reading.	Ballistic Throw.
0.641	23.92
1.221	6.67

The iron was demagnetized and the field built up in two steps:

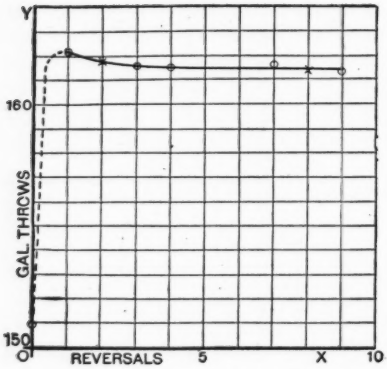


FIGURE 16. Set V: B 13,500: first magnetization; ○ indicates 1-step reversals; × 5-step reversals.

Amperemeter Reading.	Ballistic Throw.
0.641	13.94
1.221	6.65

TEST OF GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.77	21.46
13.77	21.44

The ballistic galvanometer showed a change of about seven parts in 2150 during the work. The average 1-step reversal calculated from the two 2-step reversals is 20.85. The current and so the field is slightly greater than for the 1-step reversals. However, it is doubtful if this would account for the difference between 20.76 and 20.85 with the flux B, at 13,000 as here. Probably the leakage due to the higher potential produced by the 1-step reversal and not taken into account for this core would make up the difference. At any rate one can be sure that for this particular core at this particular value of B the flux change due to two steps is not less than that due to one.

SECOND SET OF DATA.

The iron was demagnetized by the transformer.

TEST OF BALLISTIC GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.85	21.76
13.85	21.75

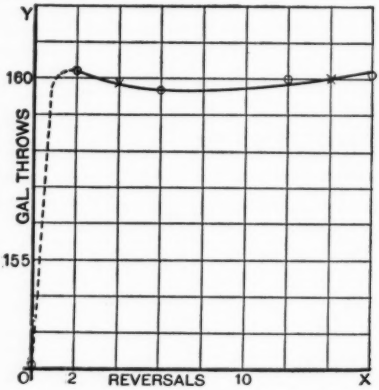


FIGURE 17. Set V: B 13,500: second magnetization; ○ indicates 1-step reversals; × 5-step reversals.

The iron was demagnetized by the transformer and the field built up in one step :

Amperemeter Reading.	Ballistic Throw.
1.218	20.81

A repetition of the process yielded the following :

Amperemeter Reading.	Ballistic Throw.
1.219	20.82

The iron was demagnetized by the transformer.

TEST OF BALLISTIC GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.78	21.54

The iron was demagnetized by the transformer and the field built up in two steps :

Amperemeter Reading.	Ballistic Throw.
0.640	13.94
1.220	6.64

The iron was demagnetized by the transformer and the field built up in two steps :

Amperemeter Reading.	Ballistic Throw.
0.640	13.96
1.219	6.58

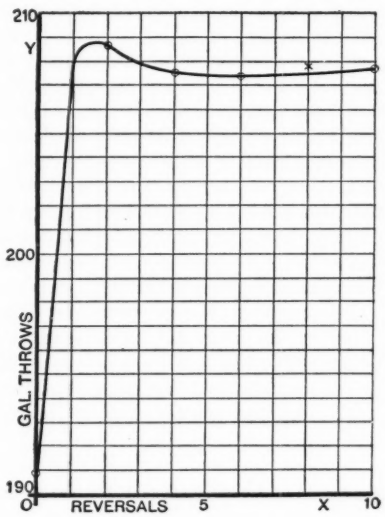


FIGURE 18. Set VI: B 19,300: first magnetization; ○ indicates 1-step reversals; × 5-step reversals.

The iron was demagnetized by the transformer.

TEST OF BALLISTIC GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.75	21.48

The iron was demagnetized by the transformer and the field built up in three steps :

Amperemeter Reading.	Ballistic Throw.
0.484	8.44
0.757	7.55
1.219	4.45

The iron was demagnetized by the transformer and the field built up in three steps :

Amperemeter Reading.	Ballistic Throw.
0.484	8.68
0.757	7.41
1.219	4.41

The galvanometer varied more than usual during the first two tests. If their average be taken to be used for the 1-step building-up intervening, the correction to be applied to 20.81 is about 0.05. That is, to make the 1-step building-up comparable to the 2-step and 3-step that follow there must be added 0.05 giving 20.86. The two 2-step processes give as the average calculated single deflection 20.81 ; the two 3-step processes 20.82. As before we have no data by which the leakage correction may be determined. However, the 2-step and 3-step processes to which it probably would not apply agree very closely. The 1-step process gives a flux change higher than the other two, but this may be due to the early variation of the galvanometer which would produce just that error in case the leakage correction were zero.

The maximum flux, B, was about 13,000.

Out of the many attempts made to obtain similar data for lower values of B, the two given above were the only ones of any value. As a sample of the results usually obtained I offer the following.

The iron was demagnetized by the transformer.

Test of Ballistic Galvanometer.

Amperemeter Reading.	Ballistic Throw.
14.26	22.22
14.26	22.21
14.25	22.17

The iron was demagnetized by the transformer and the field built up in one step :

Amperemeter Reading.	Ballistic Throw.
11.00	20.71

Four repetitions of the demagnetization and building-up of the current gave as four successive results those recorded.

Amperemeter Reading.	Ballistic Throw.
11.00	20.81
10.99	20.55
10.98	20.51
10.98	20.76

The galvanometer was not tested at the end of this set but on the next day it was found to be the same to within 0.1 of one per cent. The comparatively wide divergence between the flux changes in the iron as indicated by the instrument are far greater than any variation in it was ever found to be. When the 1-step process yields such heterogeneous results, it is not possible to draw any decided conclusions by comparing them with 2- or 3-step processes of magnetization. Taking an average in a case like this introduces an average error of $1\frac{1}{2}$ per cent at the start. Consequently all such data were discarded.

One magnetization differs from the next only in the effects produced by the previous history of the iron. We may divide that into two parts : (1), the previous magnetizations, (2), the previous demagnetizations. If the variations were due to the former, we should expect at least that there would be a continuous change and not the jumps back and forth which were often more pronounced and numerous than those recorded above. In other words, a continuous rise or fall in the flux induced would not be unexpected ; but an alternation of the two, giving wavy curves no two of which can be superposed for the same maximum fields, leads one to suspect that some disturbing element enters which is more potent than the previous magnetization.

The demagnetization seems to be that element. Only by chance is it twice the same. In one instance it may consist of 500 reversals with a maximum field of 3, 260 with a maximum field of 2.8, 800 with a maximum field of 2.5, and so on ; in the next instance it may consist of 200 reversals with a maximum field of 3.1, 400 with a maximum field of 2.9, 350 with a maximum field of 2.6, and so on. The motion of the secondary, which could not be made continuous and of which the various small distances moved were by no means equal, would give just this sort of thing. To assume that such a variation in the process should not have its effect on the non-magnetic condition in which the iron is left is hardly safe. In fact, the results obtained when everything except this process is constant are so variable as to indicate in all probability that the cause of the variation lies here.

The trouble with this method led to one somewhat similar to that used on core I. The iron was demagnetized and then carried around a hysteresis cycle with a constant maximum field for any desired number of times. It was stopped at some point between the two maximum fields, brought to a zero inducing field by simply breaking the circuit, and carried on in the direction in which it was going originally to the peak of the hysteresis curve in one step. If the flux change is always the same when the one step is repeated, it is to be inferred that the one-step replacing a larger number does not have any appreciable effect on the

fourth or fifth hysteresis cycle following, assuming that that is the number introduced between the two 1-step processes. If in continuing the work two steps be introduced in place of the one and they are in turn always the same, the same conclusion can be drawn in regard to their influence. If finally the flux changes produced by the 1-step and 2-step processes were identically equal, it is evident that, when the iron is retracing each time the same hysteresis curve, it makes no difference whether that part of the curve tested be passed over in two steps or one.

For a maximum flux of 13,000 the following data was obtained in the manner just described.

The iron was demagnetized.

TEST OF BALLISTIC GALVANOMETER.

Amperemeter Reading.	Ballistic Throw.
13.75	21.30
13.77	21.35

The iron was carried through 14.5 hysteresis cycles of forty-four steps each and back on the last half of the 15th until H was about 1.2. The field was then reduced to zero and the flux change observed on raising it to its full value in one step.

Amperemeter Reading.	Ballistic Throw.
1.220	21.89

The iron was carried through 4.5 cycles; the next half cycle was treated as above:

Amperemeter Reading.	Ballistic Throw.
1.222	21.98

The iron was carried through 4.5 cycles; the next half cycle was treated as above:

Amperemeter Reading.	Ballistic Throw.
1.223	21.92

The iron was carried through 4.5 cycles; the next half cycle was treated as above:

Amperemeter Reading.	Ballistic Throw.
1.224	21.96

The iron was carried through 4.5 cycles; the next half cycle was treated as above except that two steps replaced the one:

Amperemeter Reading.	Ballistic Throw.
0.760	17.92
1.223	3.92

After 4.5 more cycles the two steps were repeated in the next half cycle :

Amperemeter Reading.	Ballistic Throw.
0.642	15.82
1.223	5.98

After 4.5 cycles the two steps were repeated in the next half cycle :

Amperemeter Reading.	Ballistic Throw.
0.642	15.81
1.223	5.90

The iron was carried through 4.5 cycles ; the next half cycle was treated as at first — one step used :

Amperemeter Reading.	Ballistic Throw.
1.223	22.02

The iron was carried through 4.5 cycles ; the one step was used in the next half cycle :

Amperemeter Reading.	Ballistic Throw.
1.223	22.00

The iron was carried through 4.5 cycles ; the one step was used in the next half cycle :

Amperemeter Reading.	Ballistic Throw.
1.222	22.07

The iron was carried through 4.5 cycles ; the one step was used in the next half cycle :

Amperemeter Reading.	Ballistic Throw.
1.223	22.11

The average of all the 1-step processes except the first gives 22.01. The calculated 1-step reversal for the first 2-step process is 22.05, for the second 22.08, for the third 21.99. The average of these three is 22.04. This differs by three parts in 2200 from the average 1-step process. Since the average error for the latter is five parts in 2200 and for the former three parts in 2200, this difference is well within the error arising from other sources, and within $\frac{1}{4}$ per cent, it is safe to say that one step and two yield the same results. It will be observed that in the case of the two steps the dividing point was not the same

for all three cases. What variation there was seems to have had no effect.

An 8-step reversal with a maximum B of 3100 was tried and compared with a 1-step reversal of the same field. The ratio of the former to the latter was as 914 to 922. By the use of a 10-step reversal and a maximum B of 8000, it was found that the 1-step reversal corresponding yielded a maximum B about 2 per cent smaller. Such an unexpected phenomenon led to the testing of the core, excited by a strong field, by means of iron filings spread on a sheet of paper directly above it. A slight consequent pole appeared at one spot. Lack of knowledge of the other factors entering into the work prevented any attempt to determine whether or not such a pole would affect the building up of the magnetic field. The core was immediately discarded.

In so far as they were consistent the results obtained from this core show that the number of steps taken in going from one magnetic condition to another is immaterial, provided the flux change be always in the same direction. The inconsistent results support my view that when a process of demagnetization intervenes between two processes of magnetization one is not at liberty to regard the first eight or ten hysteresis cycles that may be passed over in the first magnetization as necessarily equal to the corresponding hysteresis cycles of the succeeding magnetization. In fact, I should hesitate to compare any two sets of readings if I had demagnetized the specimen between the two.

If one were to take the trouble to go through exactly the same process in each demagnetization, that is, use exactly the same number of steps, reverse the field the same number of times, and see to it that the field maxima were always the same in both order and magnitude for the corresponding steps, it is presumable that in time one could get the iron into such a condition that consistent reversal-flux curves similar to those given for core I would be obtained. Then one would be justified in comparing the flux change produced by any given reversal with the corresponding flux change produced after the next demagnetization. Such a procedure would be extremely laborious. However, it is not inconceivable that certain parts of the demagnetization have a greater effect than others on the final non-magnetic condition and that attention to those alone would be sufficient to assure consistent results. There is an opportunity here for further research.

The Investigation of Toroid III.

The amount of iron in toroids I and II and as a consequence the time required for the building up of the current are, even for low voltages, comparatively small. Toroid III, on the other hand, supplies conditions more nearly comparable to the large, solid magnetic circuit used at first. With an applied voltage just sufficient to produce a medium flux density in the iron, approximately two seconds would elapse before the amperemeter in the primary circuit, Figure 3, would come to rest. To make sure that no small effects were masked by the size of I and II, III was tested in the same manner.

The circuit, Figure 3, remained unchanged in every respect save one, the ballistic galvanometer. The slow flux change in III required the use of an instrument having a much longer period. Recourse was had to one of the types used by Professor Peirce[16]; the new galvanometer constructed differed from the old in that the balls supported by the projecting rods were replaced by an aluminium disk weighted at the circumference by a brass ring, Figure 19 (Plate). The period of this heavy system was approximately five minutes; and the error introduced when the flux change was continuous and uniform for 20 seconds, 0.7 of one per cent; that is, the observed throw would be 0.993 times the true throw.

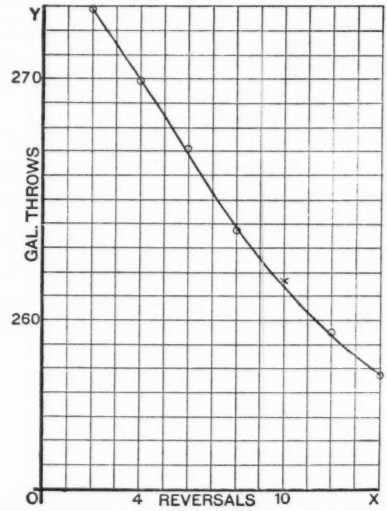


Figure 19. The value of B is 3000: the × indicates 24-step reversals, the ○ 1-step reversals.

The same care in manipulation that applied to the earlier instrument was necessary here. In fact the task of bringing the suspended

[16] These Proceedings, **44** (1909).

system absolutely to rest was no small one and yet extremely important for accurate measurements.

The data for three curves was obtained with the maximum flux densities respectively of 800, 7650 and 14,000 per square centimeter. Since the method was almost exactly similar to that employed in the case of toriods I and II, it seems worth while to note only the difference. This lay in the demagnetization; for toroid III it was carried out wholly by the reversing switch, N (Figure 3), and the rheostat or resistance cells, R and RG.

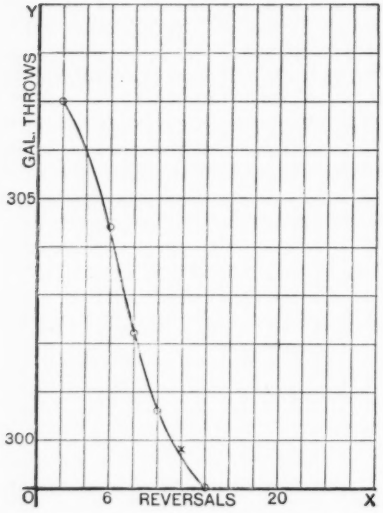


FIGURE 20. The value of B is 7650: the × indicates 22-step reversals, the ○ 1-step reversals.

The accuracy with which the long-period galvanometer could be handled was fully as great as that of the shorter. The only error introduced lay in the 0.7 of one per cent; and this was eliminated to a considerable extent. For while about 0.7 of one per cent of the throw would be lost when 1-step reversal was taken, a corresponding loss occurred in the reversals consisting of a larger number of steps, for the same field reversed. It was found that a large proportion of these small steps required about 20 seconds for their completion; as a consequence their sum would be less than the true sum. From observations as to the time in the two instances and the size of the throws I should regard it as very probable that at least half the error was cancelled by this introduction of the same inaccuracy in the two cases compared.

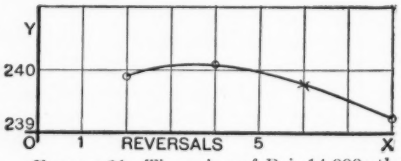


FIGURE 21. The value of B is 14,000: the × indicates 28-step reversals, the ○ 1-step reversals.

The three curves, Figures 19, 20 and 21, show the results of the investigation.

Evidently the 24-, 22- and 28-step reversals fall very nearly on the corresponding 1-step curves and are for all practical purposes equal in their flux change to the 1-step reversals.

Some of the peculiarities that appeared in the early curves of toroids I and II do not appear in these curves so prominently. However, III has been magnetized a large number of times in previous investigations and could not be expected to yield other than the results actually obtained.

Summary.

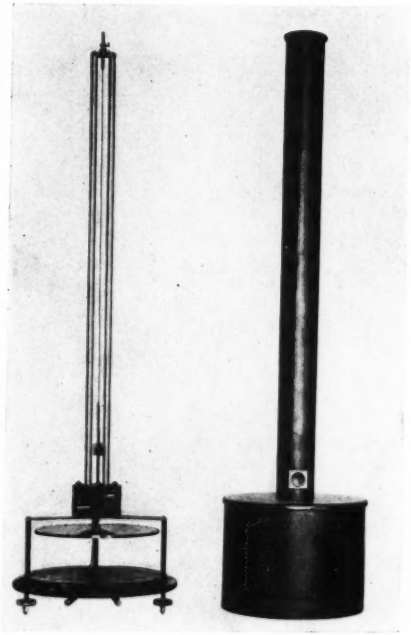
The uniformity of the results for all three toroids leads to the conclusion that, in the early stages of its magnetic history, the condition of the iron is constantly changing. During this stage of transition no given condition can be repeated by any of the ordinary methods of demagnetization and remagnetization; but as the mass is subjected again and again to the magnetizing process it attains more and more nearly to a condition such that, for all practical purposes, any magnetic state may be repeated as often as desired.

The process of demagnetization affects, by the manner in which it is carried out, the first few hysteresis curves that follow. This effect, in so far as the present investigation determined its extent, consists in a change in the maximum induction attained when the maximum field for the particular curve in question is applied.

The various stages through which the iron passes during its early magnetic history are the more numerous for the low flux densities and disappear almost completely as the point of saturation is approached. It is possible that, if one started with a high flux density and came down to the lower, another set of phenomena might appear.

The work on the large solid magnet showed conclusively that the form of the hysteresis curve depended upon the number of steps employed. The corresponding experimentation on finely divided masses, both large and small, indicated that the hysteresis cycle was not affected by the number of steps. Such was found to be the case in three distinct specimens of iron; for wherever the curves could be exactly determined, the points derived from the two methods of procedure, one by a small number, and the other by a large number of steps, fell, within 0.1 of one per cent, on a smooth curve. An obvious reconciliation of the two results lies in regarding the eddy currents, and not any inherent property of the iron, as responsible for the observed

variations in the hysteresis curve. In other words, whatever variation exists due to a special property of the iron seems to amount to less than 0.001 of the total flux change.

In general, therefore, any method of obtaining an hysteresis curve of finely laminated iron will permit one to forecast its future action. It is assumed, of course, that we have carried it past the transitional stage. On the other hand, for solid masses of iron that method should be employed which corresponds as nearly as possible to the future working conditions.

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